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On the range of spallation products

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With 6 figures in the text

1. Introduction

The reaction between an energetic particle and a nucleus can be thought of as occurring in two steps. In the first part of the reaction a nucleon cascade is developed inside the nucleus. As a result of this cascade a few high energy nucleons may be knocked out of the nucleus leaving this with a certain excitation energy. The residual nucleus then loses all its excitation energy by evaporation of particles (neutrons, protons, deuterons, alpha-particles, etc.) or emission of gamma-rays in the second part of the reaction. After this evaporation a spallation product, radioactive or stable, remains. Although a large part of the linear momentum imparted to the system by the projectile may be carried away by the fast nucleons in the first stage of the process, the residual nucleus will also get its share of the momentum available, i.e. it gets a certain recoil. The linear momentum of the residual nucleus will change during the evaporation process, but since the particles are usually given off with low kinetic energy and, besides, are evaporated isotropically, the nucleus should retain a large part of its linear momentum. One might therefore expect the spallation product to have a certain kinetic energy and consequently a certain range in the material present.

The range of the spallation products can be utilized for separation purposes. One can, for instance, catch the recoils on a foil placed in the vicinity of the target. Another possibility is to irradiate a mixture of two powdered components, namely the target proper and a suitable catcher into which spallation products could penetrate on leaving the mother grain [1].

Very few measurements of the ranges of spallation products from high energy reactions have been published [2, 3]. Ranges of the order of a few tenths of a micron have been found.

In the present article, an estimate of the ranges to be expected for the spallation products is given. The estimate is based on an investigation of the nucleon cascade and the subsequent particle evaporation using the Monte Carlo technique.

2. Linear momentum of the residual nucleus

2. 1. *Kinetic energy distribution*

The first stage of a spallation reaction can be reasonably well understood in terms of a nucleon-nucleon cascade inside the nucleus [4]. The results of such a

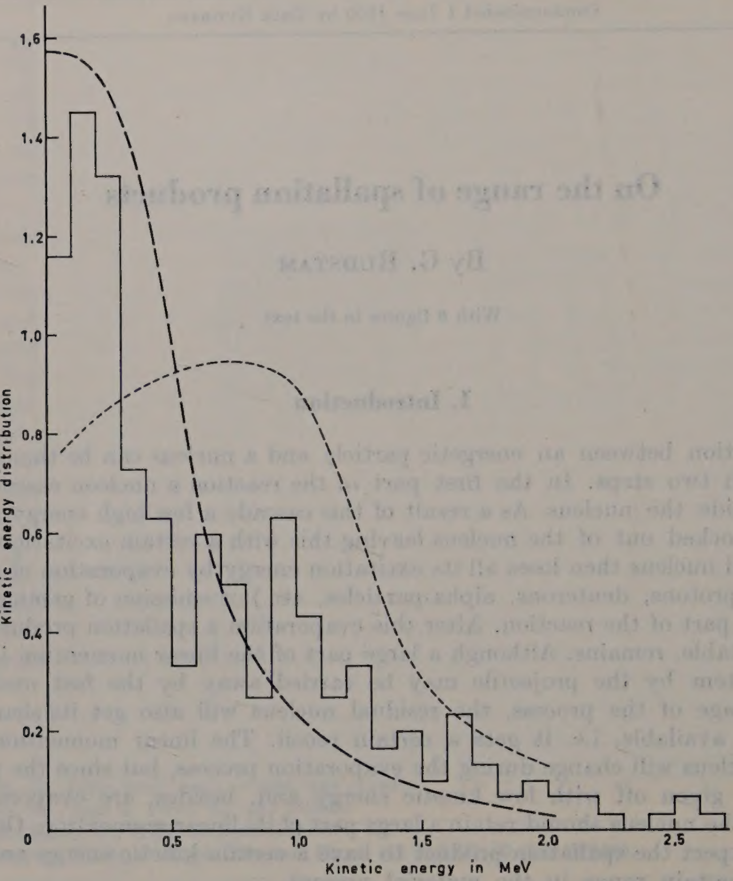

Fig. 1. Kinetic energy of the residual nuclei. Block diagram, all nuclei. Broken curve, nuclei excited to 10–30 MeV. Dotted curve, nuclei excited to 40–70 MeV.

cascade can be calculated using the Monte Carlo technique. An analysis of this type [5] designed for the study of the reaction between a proton of energy 170 MeV and an arsenic nucleus has been extended to give also the linear momentum of the residual nucleus. From the Monte Carlo analysis the linear momenta of the prompt particles leaving the nucleus as a result of the cascade are known. The difference between the momentum of the impinging proton and the momenta of the knock-ons is interpreted as the momentum taken up by the residual nucleus. In the original calculation 470 protons were followed, out of which 315 initiated a nucleon cascade within the nucleus. In each case the kinetic energy and direction (with respect to the incoming proton) of the residual nucleus was evaluated.

The block diagram in Fig. 1 shows the kinetic energy distribution. The average energy was found to be 0.73 MeV. The correlation between the kinetic energy and the excitation energy of the residual nucleus is shown in Fig. 2. The average kinetic

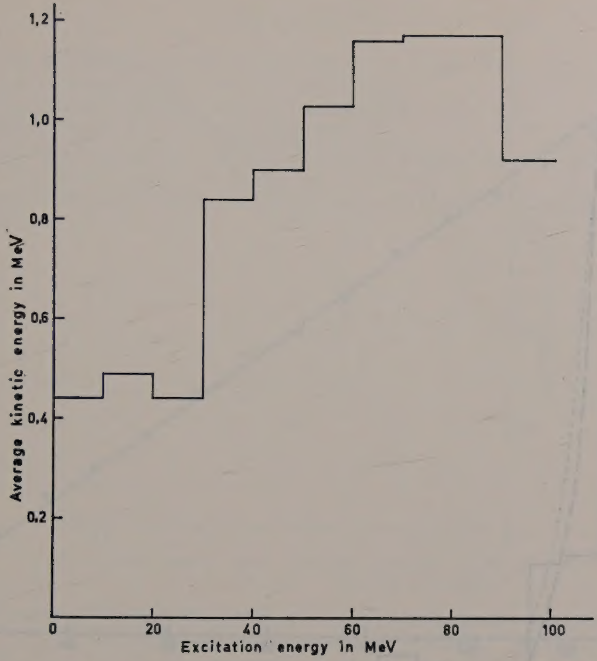

Fig. 2. The average kinetic energy of the residual nuclei *versus* their excitation energy.

energy increases with increasing excitation energy. There is, however, a wide spread in the kinetic energy distribution for a given excitation energy, as indicated in Fig. 1 for the excitation energy intervals 10–30 MeV (broken curve) and 40–70 MeV (dotted curve.)

2.2. *Angular distribution*

The angular distribution (laboratory system) of the residual nuclei is shown in Fig. 3 (block diagram). The distribution is strongly peaked in the forward direction. Furthermore, there is no great difference between fast and slow nuclei. The broken curve of Fig. 3 corresponds to kinetic energy < 0.5 MeV and the dotted curve to kinetic energy > 0.5 MeV. Both distributions are very similar.

3. Spallation products

3.1. *Range–energy relation*

The relation between kinetic energy and range for energetic particles passing through matter has been treated by Bohr [6]. By applying the proper range formula [7], it is found that the average kinetic energy of the residual nuclei, 0.73 MeV, corresponds to the range 0.53 μ in arsenic.

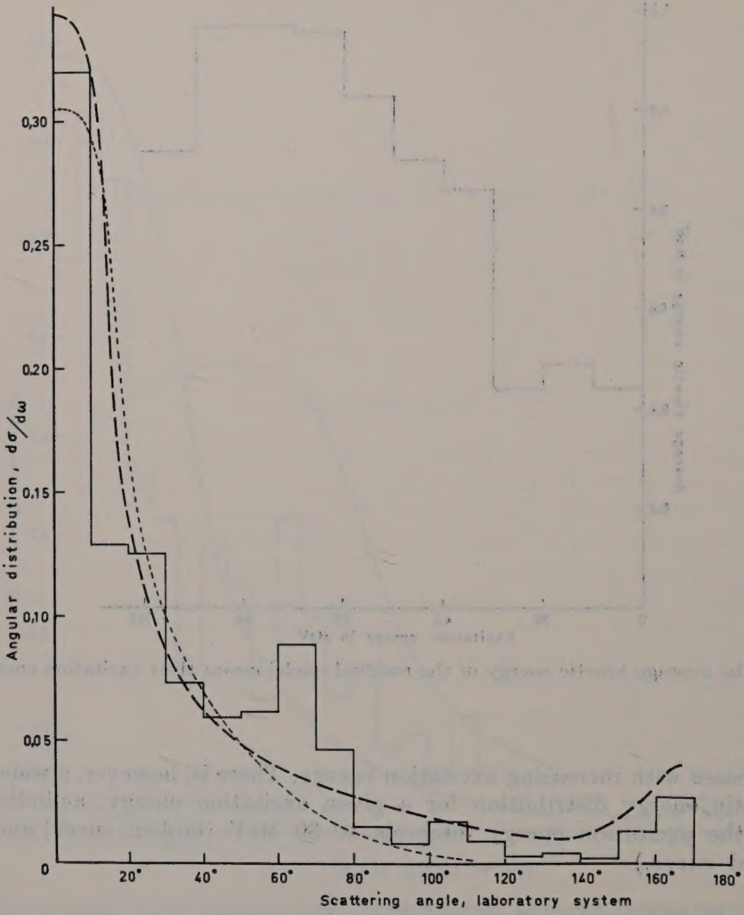

Fig. 3. Angular distribution of the residual nuclei. Block diagram, all nuclei. Broken curve, nuclei with kinetic energy < 0.5 MeV. Dotted curve, nuclei with kinetic energy > 0.5 MeV.

3.2. *The range of spallation products*

A close connection exists between the mass number of the spallation product formed in a given nuclear reaction and the excitation energy of the residual nucleus. This is evident from Fig. 4, where the average mass difference between the residual nucleus and the spallation product has been plotted *versus* this excitation energy. The corresponding distributions are shown in Fig. 5 for the excitation energies 35 MeV (solid curve) and 95 MeV (broken curve). These results are obtained from the evaporation calculation of reference [5]. Assuming now that the linear momentum of the residual nucleus is retained in the final spallation product, the range of the different spallation products as a function of the difference between the mass number of the target and that of the spallation product[1] can be estimated using the results of Figs. 2 and 4 and the range–energy relationship. The result

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[1] The number of cascade particles per reaction is taken to be 2.3.

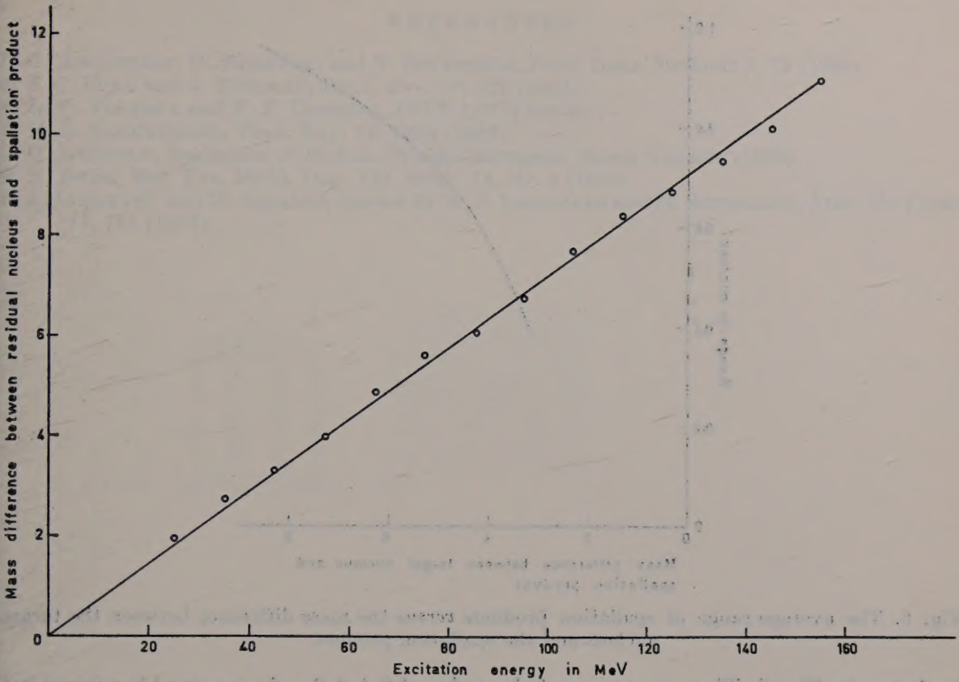

Fig. 4. The average mass difference between the residual nucleus and the spallation product *versus* the excitation energy of the residual nucleus.

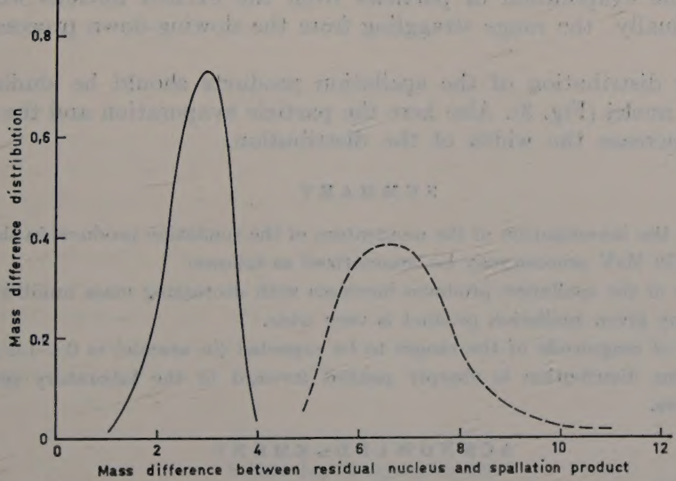

Fig. 5. Distribution of mass differences. Solid curve, excitation energy 35 MeV. Broken curve, excitation energy 95 MeV.

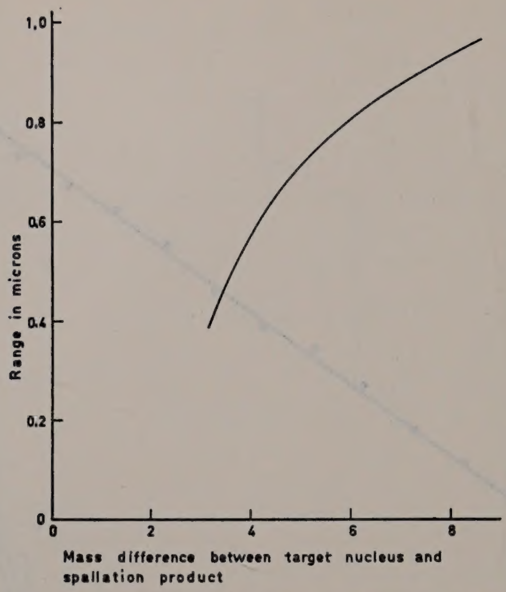

Fig. 6. The average range of spallation products *versus* the mass difference between the target nucleus and the spallation product.

is shown in Fig. 6. The ranges are of the order of 0.4–1.0 μ, in reasonable agreement with experimental data. It is found that, on the average, the range of a spallation product increases with increasing difference between the mass number of the target and that of the spallation product. This is in accord with qualitative experiments [1]. The spread in range around the average value is expected to be very large, however. First of all, the kinetic energy spread of the residual nuclei is very large (cf. Fig. 1). The evaporation of particles from the excited nucleus will enhance this spread. Finally, the range straggling from the slowing-down process is appreciable [7].

The angular distribution of the spallation products should be similar to that of the residual nuclei (Fig. 3). Also here the particle evaporation and the straggling will tend to increase the width of the distribution.

SUMMARY

The results of the investigation of the momentum of the spallation products in the spallation of arsenic with 170 MeV protons may be summarized as follows:

(*a*) The range of the spallation products increases with decreasing mass number. The range distribution of any given spallation product is very wide.

(*b*) The order of magnitude of the ranges to be expected (in arsenic) is 0.4–1.0 μ.

(*c*) The angular distribution is sharply peaked forward in the laboratory system for all spallation products.

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